Ministry of Transportation
Ontario

REPORT EM - 89

LABORATORY EVALUATION OF RECYCLED HOT MIXES

(VOLUME 2)

MOISTURE SUSCEPTIBILITY AND STRENGTH CHARACTERISTICS

E ngineering
M aterials
O ffice

LABORATORY EVALUATION OF RECYCLED HOT MIXES (VOLUME 2)

MOISTURE SUSCEPTIBILITY AND STRENGTH CHARACTERISTICS

BY

P. E. JOSEPH

K. K. TAM

D. F. LYNCH

BITUMINOUS SECTION

ENGINEERING MATERIALS OFFICE

MINISTRY OF TRANSPORTATION OF ONTARIO

APRIL 1989

ISBN 0-7729-5894-7

ABSTRACT

The investigation reported herein examined the moisture susceptibility and strength characteristics of recycled hot mixes and compared them with those of the conventional mix (HL4). The moisture induced damage was evaluated using the method given in reference [11]. The severity of the moisture damage was assessed by the ratio of the tensile strength (TSR) of the wet specimen to that of the dry specimen. The strength characteristics include the mix stability and the recoverable deformation of the mix at various temperatures due to dynamic loading. The stability was evaluated on the basis of a) shear strength criterion expressed by Mohr-Coulomb failure law, and b) Marshall criteria. The recoverable deformation was measured in terms of resilient modulus at three test temperatures (5, 25, 40°C).

The results indicate that both recycled mixes and HL4 mix have good resistance to damage due to moisture. However, with respect to stability and deformation, recycled hot mixes have relatively higher compressive and shear strengths which indicate that they are less susceptible to deformation due to densification and shear.

ABRÉGÉ

Ce rapport porte sur l'examen de la sensibilité à l'humidité et des caractéristiques de résistance des mélanges recyclés préparés à chaud, en comparaison avec celles des mélanges conventionnels (HL4). On a évalué les dommages causés par l'humidité induite à l'aide de la méthode donnée en référence [11]. La gravité des dommages causés par l'humidité a été établie grâce au rapport de résistance à la traction entre l'échantillon humide et l'échantillon sec. Les caractéristiques de résistance comprennent la stabilité du mélange et la déformation récupérable du mélange à diverses températures sous charge dynamique. On a évalué la stabilité en fonction de : a) la résistance au cisaillement telle que définie par la loi de Mohr-Coulomb, et d'après b) le critère de Marshall. On a mesuré la déformation récupérable en termes de module d'élasticité, à trois températures d'essai, soit 5, 25 et 40°C.

Les résulats indiquent que les mélanges recyclés préparés à chaud et les mélanges HL4 présentent une bonne résistance aux dommages causés par l'humidité. Cependant, pour ce qui est de la stabilité et de la déformation, les mélanges recyclés préparés à chaud possèdent une résistance à la compression et au cisaillement plus grande, ce qui prouve qu'ils sont moins sensibles à la déformation causée par le compactage et le cisaillement.

CONTENTS

	PAGE
1 INTRODUCTION	1
2 SCOPE AND OBJECTIVES	1
3 CURRENT STATE OF KNOWLEDGE	2
3.1 CURRENT KNOWLEDGE ON MOISTURE INDUCED DAMAGE	2
3.2 CURRENT KNOWLEDGE ON MIX STABILITY	5
3.2.1 MARSHALL STABILITY	5
3.2.2 MOHR-COULOMB FAILURE LAW	5
3.3 CURRENT KNOWLEDGE ON RESILIENT MODULUS	6
4 EXPERIMENTAL INVESTIGATION	7
4.1 SAMPLE PREPARATION	7
4.2 MOISTURE INDUCED DAMAGE TEST	8
4.3 TENSION, COMPRESSION AND MARSHALL STABILITY TESTS	8
4.4 RESILIENT MODULUS TEST	9
5 ANALYSIS OF TEST RESULTS	9
5.1 MOISTURE INDUCED DAMAGE TEST	9
5.2 MIX STABILITY	10
5.2.1 MARSHALL TEST RESULTS	10
5.2.2 RESULTS OF MOHR-COULOMB FAILURE ANALYSIS	12
5.2.2.1 SHEAR STRESS	12
5.2.2.2 COMPRESSIVE STRESS	12
5.2.2.3 TENSILE AND COHESIVE STRENGTHS	13
5.3 RESILIENT MODULUS	14

CONTENTS (contd.)

	PAGE
6 CONCLUSIONS AND RECOMMENDATIONS	16
6.1 CONCLUSIONS	16
6.3 RECOMMENDATIONS	17
REFERENCES	18
ACKNOWLEDGEMENT	19

LIST OF FIGURES

1 MOHR DIAGRAM

2 TENSILE STRENGTH COMPARISON OF DRY AND WET MIXES

3 TSR COMPARISON OF VARIOUS MIXES

4 MARSHALL STABILITY COMPARISON OF VARIOUS MIXES

5 SHEAR STRESS COMPARISON OF VARIOUS MIXES

6 COMPRESSIVE STRESS COMPARISONS OF VARIOUS MIXES

7 RELATIONSHIP BETWEEN TEMMPERATURE AND RESILIENT MODULUS OF PLANT MIXES

8 RELATIONSHIP BETWEEN TEMPERATURE AND RESILIENT MODULUS OF LABORATORY MIXES

9 COMPARISON OF RESILIENT MODULI OF VARIOUS MIXES AT DIFFERENT TEMPERATURES

10 RELATIONSHIP BETWEEN TEMPERATURE AND POISSON'S RATIO OF PLANT MIXES

11 RELATIONSHIP BETWEEN TEMPERATURE AND POISSON'S RATIO OF LABORATORY MIXES

LIST OF TABLES

1 MIX DESIGN PROPERTIES AND PLANT CHECK RESULTS OF RECYCLED HOT MIXES

2 AADT FOR DIFFERENT RHM TEST SECTIONS

3 RECOVERED ASPHALT BINDER PROPERTIES

4 AGGREGATE DESCRIPTION FOR VARIOUS MIXES

5 AGGREGATE GRADATIONS FOR HL4 AND RHM MIXES

6 EXPERIMENTAL DESIGN FOR MOISTURE INDUCED DAMAGE TESTS

7 EXPERIMENTAL DESIGN FOR TENSION, COMPRESSION, AND MARSHALL STABILITY TESTS

8 EXPERIMENTAL DESIGN FOR RESILIENT MODULUS TESTS

9 MOISTURE INDUCED DAMAGE TEST RESULTS

10 MARSHALL TEST VALUES FOR VARIOUS ASPHALT MIXES

11 COMPARISON OF SHEAR DEFORMATION PARAMETERS

12 STATIC AND DYNAMIC LOAD VALUES FOR RESILIENT MODULUS TESTING

13 RESILIENT MODULUS AND POISSON'S RATIO VALUES FOR VARIOUS MIXES

1 INTRODUCTION

To follow up the field investigation carried out by the Ministry of Transportation, Ontario [1] on the performance of recycled asphaltic concrete pavements, a material characterization study was undertaken to evaluate in the laboratory the moisture susceptibility and strength characteristics of recycled hot mixes containing various amounts of RAP materials in comparison to a virgin mix. The strength characteristics include the stability, and the recoverable deformation of the mix under dynamic loading at various temperatures. Although initial field data based on seven test sections indicated hitherto no such concerns with respect to stability and moisture induced damage, it was considered important to carry out an objective comparative evaluation study to gain better understanding of the effect of different factors such as recycling ratio, rejuvenating agent, aggregates etc. on moisture susceptibility, stability, and resilient characteristics of recycled hot mixes and a conventional mix. The study also examines the feasibility of using shear strength criterion to supplement Marshall test as there have been concerns with adequacy of mixtures designed according to Marshall method to withstand heavy traffic loads in hot environments.

2 SCOPE AND OBJECTIVES

The primary objectives of this study are:

1) To evaluate in the laboratory the moisture susceptibility of various recycled hot mixes used in different regions of Ontario,

2) To study the effect of recycling ratio and rejuvenating agent on stability and resilient characteristics of the recycled hot mixes,

3) To investigate the feasibility of using shear strength expressed by Mohr-Coulomb failure law to supplement Marshall criteria for mix design.

3 CURRENT STATE OF KNOWLEDGE

3.1 CURRENT KNOWLEDGE ON MOISTURE INDUCED DAMAGE

A survey of related literature indicates that the most common form of moisture induced pavement damage is asphalt stripping and it occurs when the moisture enters into the pavement either during construction or during the service life of the pavement [2]. Several mechanisms by which water displaces asphalt from the aggregate surface have been postulated and their descriptions can be found in a number of publications [3,4,5].

References [4,5] present the various aspects of the problem and indicate that interfacial tensions between pure asphalt, water and aggregate are such that stripping is inevitable whenever the three faces meet. However, Thelen [4] noted that if the absorbed water is removed completely, an inseparable asphalt aggregate bond can be restored. The complete removal of water from the aggregate is indeed a difficult task, particularly with respect to aggregates of hydrophilic nature. This requires heating the aggregate to very high temperatures for a considerable period of time. The next alternative is to prevent or retard the penetration of water into the asphalt. Several theories have been postulated to explain how the water enters the asphalt and some of

them, namely "osmosis", "formulation of pinholes", and "emulsification" are discussed in reference [4,6,7].

In Ontario, asphaltic concrete mixes are designed to have low voids in order to minimize, if not prevent moisture damage in addition to obtaining durability and other engineering properties. Some agencies use antistripping additives to achieve the same objective. Other agencies adopt different procedures such as disallowing the use of known hydrophilic aggregates, washings of aggregates, precoating aggregates with bitumen or diluents prior to mixing with asphalt, etc.

It is also useful to note that there may be some unforeseen circumstances that contributing to stripping; for example, construction methods by which water is trapped within the pavement or unexpected increase in traffic load or presence of moisture vapour in arid climates can sometimes cause stripping. In all the above mentioned cases, a series of laboratory tests need to be performed in order to identify the potential of aggregates to stripping and consequently to measure the effectiveness of the proposed preventive steps. Several testing procedures are used for this purpose and the most of them can be grouped into one of four categories:

1) Coating tests,
2) Stripping tests,
3) Immersion-compression tests,
4) Tensile splitting tests.

The coating test is used to evaluate the ability of the binder to satisfactorily cover wet aggregate. The aggregate in this case is wetted before it is mixed

with the binder and evaluated for the amount of coverage using Ottawa sand or standard trap rock.

The stripping test is done by immersing previously coated aggregates in water and allowing them to soak for period of time. Then, the surface area of the aggregate still coated with bitumen is determined. The criterion that must be met in the above two tests varies with severity of the test, usually in the range between 90-100% [2].

The immersion-compression test (on compacted mixtures) is used to determine the effect of water on cohesion. The influence of water is evaluated by determining the strength reduction as a result of moisture conditioning.

The indirect tension test is the major procedure used to assess the moisture damage of both pavement cores and moisture-conditioned laboratory specimens. Basically there are four different procedures available. One has been developed by Jimenez [8], the other by Lottman [9], and the third one by Tunnicliff [10] and the last method by the NCHRP as described in reference [11]. In all cases, Marshall specimens 101mm in diameter and 62mm in height were used. To distribute the load and maintain a constant loading area, the compressive load was applied through a 12 mm wide steel loading strip that was curved at the interface with the specimen and had a radius equal to that of the specimen. This loading configuration develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametral plane which ultimately causes the specimen to fail by splitting or rupturing along the vertical diameter.

3.2 CURRENT KNOWLEDGE ON MIX STABILITY

According to the Asphalt Institute report [12] stability is defined as the resistance to deformation of asphalt paving mixtures under imposed loads. It is an important property which measures the adequacy of the mix to carry the type and amount of traffic. Factors that influence stability are aggregate surface texture, shape and gradation, quantity, quality and grade of asphalt cement, and mix density. The required resistance to internal shear deformation results from a combination of aggregate friction and asphalt cohesive forces. For a stable mix, an aggregate must have the necessary surface texture, shape, and gradation to provide resistance to internal shear forces. As well, the mix must have proper asphalt cement content which provides enough cohesive strength to resist separation of the particles. Among different methods of determining the stability of a mix, only two of them were used in this investigation, the Marshall test and shear strength criterion expressed by Mohr-Coulomb failure law.

3.2.1 Marshall Test

The Marshall test method was originally formulated by Bruce Marshall and was subsequently improved through extensive research and correlation studies. The Marshall test procedures have been standardized by the American Society of Testing and Materials and the detailed description of the testing procedures can be found in ASTM D1559.

3.2.2 Mohr Coulomb Failure Law

The resistance to shear deformation of asphalt mixes, can be determined using the Mohr-Coulomb model which relates the shear strength to normal stress by the following equation [13]:

$$S = C + \sigma_n \tan \Phi$$

where, S = shear strength,

C = cohesion (interparticle attraction)

σ_n = normal stress on the critical plane of failure

Φ = angle of internal friction

The model determines the maximum shear stress at which rupture will occur along a plane. According to Mohr, the failure is not caused by the extreme stress of one type (normal or shearing stress) but by a critical combination of both. The path of the critical combinations of the normal stress and shearing stress is determined by Mohr circles and it is called the Mohr failure envelope (Figure 1). Although this envelope is a curve, it is usually approximated by a straight line for practical purposes. The magnitude of the shearing resistance that may be developed by the asphaltic concrete is dictated by the angle of internal friction (Φ) and the normal force on the plane of failure. These in turn depend on the tensile and compressive stresses of the material.
The shear strength is estimated indirectly by plotting Mohr circles using maximum compressive stress and tensile stress as shown in Figure 1.

3.3 CURRENT KNOWLEDGE ON RESILIENT MODULUS

Resilient modulus is used to characterize recoverable deformation of bituminous materials during dynamic loading. It is defined as the ratio of stress range to recoverable strain. The primary factor which influences resilient modulus is the temperature and consequently it is being used to study the susceptibility of asphaltic concrete mixture to temperature. The

theoretical basis for the development of resilient modulus testing is given in the manual [14] and the testing procedure can be found in ASTM D4123.

4 EXPERIMENTAL INVESTIGATION

4.1 SAMPLE PREPARATION

Test samples were prepared according to procedures given in ASTM D-1561 (Cylindrical), ASTM D3202 (Beams), and MTO Laboratory standards, LS-261 (Marshall Briquettes). Materials for standard HL-4 mix were selected according to the mix design procedure of the Ministry of Transportation [15]. For recycled hot mix specimens, plant mixed materials and laboratory mixed materials were used. The former were obtained directly from batch or drum plants and the latter were prepared in the laboratory using aggregates, reclaimed asphalt pavement (RAP) materials and asphalt cement as supplied from the field. However, for Contracts 81-74 and 82-04 the source of supply of binders for lab mixes was different from that for plant mixes because of non-availability of the binders as supplied from the field.

Mix design requirements for recycled hot mix are given in Table 1, and the traffic growth for each test section is given in Table 2. Numbers within parentheses of Table 1 are the plant check results of all the contracts under investigation.

Because of time constraints, the laboratory tests were limited to samples and materials obtained from five contracts only. The selected Contracts were 81-224, 82-19, 83-43, 81-74 and 82-04 which represent different regions and cover a wide range of asphalt cement grades and recycling ratios. The asphalt binder

properties of the selected recycled hot mixes are given in Table 3. As well, the results of petrographic and sieve analyses of aggregates used for each contract are provided in Tables 4 and 5.

4.2 MOISTURE INDUCED DAMAGE TEST

In this study, the moisture induced damage of paving mixtures was evaluated using the test method given in reference [11], which outlines the procedures for preparing and testing of specimens. This method is basically similar in concept to the methods developed by Lottman and Tunnicliff with a little variation in the procedure involved for specimen saturation and moisture conditioning. The specimens were compacted to void levels between 6-8% range. For each mix type, two sets of specimens having approximately equal void content were prepared; one was maintained dry and the other set was partially saturated with water (between 55-80%) and moisture conditioned for 24 hrs. Each set consists of four specimens; two were tested dry and the other two were tested after partial saturation and moisture conditioning. Tensile strengths of specimens in each set was determined by the indirect tensile splitting test. The severity of moisture damage was indicated by the ratio of the tensile strength (TSR) of the wet specimen to that of the dry specimen. A value of 75% or more for TSR is considered acceptable [2,16]. A factorial arrangement for the testing program is given in Table 6.

4.3 TENSION, COMPRESSION AND MARSHALL STABILITY TESTS

Direct tension tests were performed at 21°C, to determine the tensile strengths, strains, and stiffnesses of different mixes. The specimen was pulled at a constant rate of extension (5mm/min) until failure occurred. The stress, strain, and stiffness at failure were recorded and the plots of stress-strain

graph were obtained. For compression tests cylindrical specimens of 101mm in both height and diameter were used to determine the compressive strengths of different mixes at 21°C. A deformation rate of 5mm/min. was selected to run the test. Two tests were carried out for each mix type. Marshall stability tests, also two for each mix type, were performed according to ASTM D1559. A complete factorial arrangements for the above tests were given in Table 7.

4.4 RESILIENT MODULUS TEST

Resilient modulus testing was performed at three temperatures, 5, 25, and 40°C according to ASTM testing procedures. A repeated haversine compressive loading of 0.1s duration at a frequency of 0.33 Hz was applied at the vertical diameter of the sample and the corresponding vertical and horizontal deformations were recorded. The test was performed on two different positions of the sample, 90 degrees apart diametrically. To ensure proper contact between the loading strip and the specimen, a minimum static load was applied throughout the test. The magnitude of this load could vary from 5 to 10N at 40°C, 10 to 40N at 25°C, and 50 to 200N at 5°C, depending on the test temperature and the specimen stiffness as subsequently shown in Table 9. A factorial arrangement for this test is given in Table 8.

5 ANALYSIS OF TEST RESULTS

5.1 MOISTURE INDUCED DAMAGE TEST

Table 6 presents the results of the experimental investigation and Figures 2 and 3 compare the tensile strengths of dry and wet specimens. It can be observed that the tensile strength ratio for all mixes are more than 75% indicating low stripping potential. It will be useful to note that the mix from

Contract 81-74 has about 0.5% antistripping agent, indicative of a previous stripping problem and the addition of an antistripping agent has been effective in improving the performance of the mix.

5.2 MIX STABILITY

5.2.1 Marshall Test Results

The results obtained on Marshall tests are presented in Table 7 and the comparison of their results is shown in Figure 4. The Marshall stability values are fairly high for all mixes (>17,000N) and flow values remain between 11-20. Higher flow values of 20 and 18.5 are obtained for plant mixes from Contracts 82-19 and 83-43. Based on Marshall stability values, both the virgin and recycled hot mixes seem to have good stability and the differences in the stability values among different mixes are in the neighbourhood of 10% or less. The relatively higher Marshall stability values for the mixes from Contracts 82-04 (22,578 N) and 83-43 (24,922 N) could be attributed to the use of high recycling ratio, and/or RAP with crushed aggregates.

Experience suggests that the Marshall stability for HL4 mixes using the Durham coarse and fine aggregates in general ranges between 13,000N and 17,000N. The reason for a higher value (21,350N) in this case may perhaps be due to the age hardening of asphalt binder in the specimens which had been prepared three years ago prior to the present testing.

It cannot be too strongly emphasized that Marshall stability value cannot provide a satisfactory measure of the actual resistance of a mix to deformation. Some improvements on the assessment based on stability have been attempted

by The Asphalt Institute which set an upper flow limit of 16 for road surfacings with heavy traffic. It recognized the fact that mixes with high flow values are more susceptible to plastic deformation. McLeod suggested a method [17] that combines both flow index and Marshall stability to form a Marshall stiffness which is defined by the following equation:

$$\text{Marshall Stiffness (MPa)} = 0.062\left[\frac{\text{Stability (N)}}{\text{Flow (0.25mm)}}\right] \qquad (1)$$

This equation was developed from the original definition for modulus of stiffness based on the theory of elasticity which is defined as follows:

$$\text{Modulus of stiffness} = \frac{\text{stress}}{\text{strain}} \qquad (2)$$

Insofar as Marshall criteria are concerned, the Marshall stability is the load (N) applied at failure over the cross section of the test briquette, which is 101.6mm (4in) in diameter and 63.5mm (2.5in) thick. Consequently, the stress referred to in equation(2) is $\frac{\text{stability (N)}}{101.6\text{x}63.5\ (\text{mm}^2)}$. The strain at failure is the flow index, which measures the decrease in units of 0.254mm over the 101.6lmm diameter of the test specimen. Therefore the strain factor in equation(2) is $\frac{0.254\text{xFlow}}{101.6}$. Substituting these terms in equation(2) gives:

$$\text{Modulus stiffness (MPa)} = \frac{\text{stability (N)}/101.6\text{x}63.5\ (\text{mm}^2)}{0.254\text{xFlow}/101.6(\text{mm})}$$

$$= 0.062\left[\frac{\text{stability (N)}}{\text{Flow}(0.25\text{mm})}\right]$$

Modulus stiffness in this case is known as Marshall stiffness because it is determined from the Marshall test. McLeod's approach indicates that virgin

mix has better stability than the recycled mixes, which is contrary to the findings based on Mohr-Coulomb hypothesis. Consequently, further research is required to develop appropriate tests to evaluate the stability of bituminous materials.

5.2.2 Results of Mohr-Coulomb Failure Analysis

The shear strength is actually obtained indirectly by plotting Mohr circles using maximum compressive stress and tensile stress as discussed in section 3.2.2. Table 8 presents a comparison of maximum shear stress, compressive stress, tensile stress, cohesive strength and angle of friction. The following observations can be made from the test results.

5.2.2.1. Shear Stress

It can be seen from Figure 5 that shear stresses for recycled hot mixes (plant and laboratory mixes) are much higher than for the HL4 mix, indicating that they have much higher resistance to rutting due to shear displacement as compared to the conventional (HL4) mix. Among recycled hot mixes plant specimens exhibit higher shear stresses than laboratory specimens. In comparison to HL4 mix the highest percentage increase (300%) in the shear stress corresponds to plant specimens from Contracts 82-04 and 83-43 and the lowest value (50% increase) corresponds to the laboratory specimen from Contract 82-19. Such increase in value of shear stress for the mixes from Contract 82-04 and 83-43 could be attributed to the use of high recycling ratio and/or RAP with crushed aggregates together with 85/100 grade asphalt cement.

5.2.2.2 Compressive Stress

All recycled plant mixes exhibit higher compressive stresses than HL4 mix. According to Figure 6, specimens representing Contracts 82-04 and 83-43 show significantly higher (150-200%) values whereas mixes from Contracts 82-19 and 81-224 show marginally higher (8-13%) values than HL4 mix. Recycled hot mix from Contract 81-74 gave moderately higher (40%) compressive strength than the HL4 mix. Reasons for such variation could be mainly due to the variability in the recycling mix ratio and the type of asphalt cement used in each mix. As regards the laboratory specimens, the values of compressive stress in general is less than the plant mixes but still exhibit higher stress values as compared to the HL4 mix with the exception of Contract 82-19. In general, the recycled hot mix specimens exhibit higher compressive strengths than the HL4 mix specimen.

5.2.2.3 Tensile and Cohesive Strengths

For perfectly bonded asphaltic concrete, the maximum tensile strength is basically equal to the cohesive strength of the binder. The tensile strength will be significantly less than the cohesive strength in the case of poorly bonded aggregate particles and the direct tension test will reveal only the adhesive strength instead of cohesive strength of the binder. The difference between the tensile strength and cohesive strength could also be due to the variability within the specimens used for testing. The test results from Table 8 indicate that the difference between the tensile strength and the cohesive strength is significant (50%) for the virgin mix and less significant (< 30%) for recycled hot mixes. This suggests that the bonding between the binder and aggregates is better in the case of recycled hot mixes than the virgin mix. However, further research is required to confirm this finding. It is also evident that the tensile stress of asphaltic concrete plays a vital role in the

stability of bituminous materials. For instance, the low shear resistance of HL4 mix is the direct result of its low tensile strength.

The final conclusion based on shear strength criterion is that the recycled hot mixes have higher shear resistance than HL4 mix. Among the recycled mixes, the one with higher recycling ratio tends to show relatively higher shear strengths. One of the shortcomings of Mohr-Coulomb model is that it doesn't take into account shear strains and therefore provides little information about displacements resulting from imposed loads.

In summary, this section provides a comparative evaluation on the stability of recycled hot mixes and HL4 mix based on two criteria; shear strength and Marshall stability. The analysis based on strength criterion confirms the common belief that recycled hot mixes in general are more stable than HL4 mix; whereas, the Marshall test results indicate no significant difference among different mixes with regard to their stability. In general, it can be concluded based on the test results that recycled mixes with higher percentage of RAP materials exhibit relatively higher compressive and shear strengths than a HL4 mix and hence have more resistance to deformation due to densification (compaction) and shear.

5.3 RESILIENT MODULUS

The resilient modulus values for all specimens were calculated at three test temperatures (5, 25 and 40°C) under repeated loading conditions as specified by the ASTM. Two tests were performed for each specimen and the results were averaged. For the specimen from Contract 82-19, no test results were obtained at 40°C because of excessive deformation of the specimen even under very

small (45N) loading conditions. During testing, an initial load of approximately 10% of the dynamic load was applied to obtain uniform deformation readout of the specimen under dynamic loading. The magnitude of the dynamic load depends on the test temperature and the type of specimen used for testing. Table 8 provides the range of values selected for initial static and dynamic loadings. The average resilient modulus and Poisson's ratio for different mixes at 5, 25, and 40°C are given in Table 9. Variation of resilient modulus with temperature for plant and laboratory mixes are given in Figures 7 and 8. As expected, the resilient moduli of all mixes decrease as temperature increases. In general, the rate of reduction in resilient modulus values with increasing temperature from 5°C to 40°C is reasonably constant for all mixes except for the laboratory mix from Contract 82-19. This mix shows a significant reduction from 5°C to 25°C and as discussed previously no value could be obtained at 40°C because of its excessive deformation.

Figure 9 compares the resilient modulus of various mixes at different temperatures. It can be seen that laboratory mixes tend to have slightly higher values than plant mixes at 40°C and the trend is reversed at 5°C and 25°C. The mix having 70 percent RAP materials (Contract 82-04) gave the highest resilient modulus at all temperatures. In general, all recycled mixes have higher resilient modulus than HL4 mix at 40°C. At 5°C and 25°C, recycled mixes from contracts 82-04 and 83-43 show significantly higher values than HL4 mix whereas, the rest of the recycled mixes exhibit more or less the same values as those of HL4 mix.

The Poisson's ratio-temperature relationships for plant and laboratory mixes are given in Figures 10 and 11, respectively, which show a greater range of

values at elevated temperatures. The higher value for Poisson's ratio at elevated temperature means higher susceptibility to permanent deformation. It can be seen that the HL4 mix typically demonstrates relatively poor resistance (high Poisson's ratio) to deformation as compared to the recycled hot mixes, particularly the mixes from Contracts 82-04 and 83-43. This finding is quite consistent with the results obtained from shear stress, compressive stress and resilient modulus tests.

Further, it is to be noted that the calculation of resilient modulus as determined by the diametral method is significantly affected by the Poisson's ratio and therefore any assumed value for Poisson's ratio (traditionally $\nu = 0.35$) for the computation of resilient modulus value is not considered acceptable.

6 CONCLUSIONS AND RECOMMENDATIONS

6.2 CONCLUSIONS

Recycled hot mixes representing five contracts from different regions of Ontario were evaluated for stability, moisture susceptibility, and resistance to deformation at various temperatures using a practical laboratory system. As well, the effect using of various amount of RAP materials for recycled hot mixes was investigated and the results were compared to that of the virgin mix. Further, the study examined the stability of the mixes using shear strength criterion based on Mohr-Coulomb failure law. The conclusions based on the results of the analysis are presented as follows.

1) The stability of recycled hot mixes based on Marshall criteria is comparable to that of the standard conventional mix. However,

compressive strength and shear strength criteria support the general belief that the recycled hot mixes have better resistance to deformation due to densification and shear than a HL4 mix. Among the recycled hot mixes, the ones with higher recycling ratio appeared to have more resistance to deformation.

2) With respect to resilient modulus, recycled hot mixes in general, have higher resilient modulus than the HL4 mix particularly at high temperature (40°C). The highest value corresponds to the mix from contract 82-04 which has 70 percent RAP materials.

3) Both HL4 and recycled hot mixes evaluated in this project indicate low potential for moisture induced damage.

6.3 RECOMMENDATION

Further research is recommended to:

1) Develop an appropriate test method that could be used on a routine basis to supplement the existing Marshall criteria for mix design of rut resistant mixes to withstand heavy traffic loads,.

2) Estimate more objectively the load range required (without trial and error) for resilient modulus testing of bituminous materials having variable stiffness values at different temperatures.

REFERENCES

1 Tam, K.K., "Recycled Hot Mixes: An Evaluation of Five Years Trend on Material Properties", Report MI-89, MTC, EMO, Bituminous Section, 1986.

2 Tunnicliff, D. G.,.and Root, R. E., "Antistirpping Additives in Asphalt Concrete - State of Art 1981", Proc., AAPT., Vol. 51, 1982.

3 Fromm, H. J., "The Mechanisms of Asphalt Sripping from Aggregate Surfaces", Proc. Assoc. Asphalt-Paving Technol. 43, 191-223, 1974.

4 Thelen, E., "Surface Energy and Adhesion Properties in Asphalt Aggregate Systems", Highway Research Board Bulletin 192, Highway Research Board, Washington, D. C., U.S.A., 1958 p.63.

5 Gzemski, F. C., McGlashan, D. W., and Dolch, W. M. L., of Committe MC-A6, "Thermodynamic Aspects of Stripping Problem", Highway Research Circular No. 18, Highway Research Board, Washington, D. C., March, 1968.

6 Mack, C., Bituminous Materials, Vol. 1, Editor: Arnold Hoiberg, New York, N. Y., U.S.A., Interscience Publishers, 1964.

7 Lottman, R. P., "The Moisture Mechanism that Causes Aspl.alt Stripping in Asphaltic Pavement Mixture", Final Report, Engineering Station, Department of Civil Engineering, University of Idaho, Moscow Idaho, U.S.A., Feb. 1971.

8 Jimenez, R. A., "Testing for Debonding of Asphalt from Aggregates", Transport Research Record 515, TRB, 1974.

9 Lottman, R. P., "Predicting Moisture-Induced Damage to Asphalt Concrete", NCHRP Report No. 192, Transport Research Board, 1978.

10 Tunnicliff, D. G., and Root, R. E., "Testing Asphalt Concrete for Effectiveness of Antistripping Additives", AAPT, Atlanta, GA, February 28-March 2, 1983.

11 Method of Test for Determining the Effect of Moisture and Anti-stripping Additives on Asphalt Concrete Paving Mixtures, NCHRP Project 10-17, 1984.

12 Educational Series No. 3 (ES-3), The Asphalt Institute, July 1979

13 Terzahi, K., "Theoretical Soil Mechanics", John Wiley and Sons Inc., New York (1944).

14 Bituminous Material Characterization Manual, Bituminous Section, Engineering Materials Office, ISBN 0-7729-3922-5.

15 Method for Design of Bituminous Mixes, Bituminous Section, Engineering Materials Office, MTC, Unpublished Report, April, 1980.

16 Maupin, G.W., "Implementation of Stripping Test for Asphalt Concrete," Transport Research Board 712, TRB, 1979

17 McLeod, N. W., "Asphalt Materials", Course Notes for Civil Engineering, Univ. of Waterloo.

ACKNOWLEDGEMENT

The authors wish to acknowledge the contribution made by Richard Raciborski towards developing the computer programming for the testing. As well, the extensive assistance of Jim Pretty and A. Weremi is greatly appreciated.

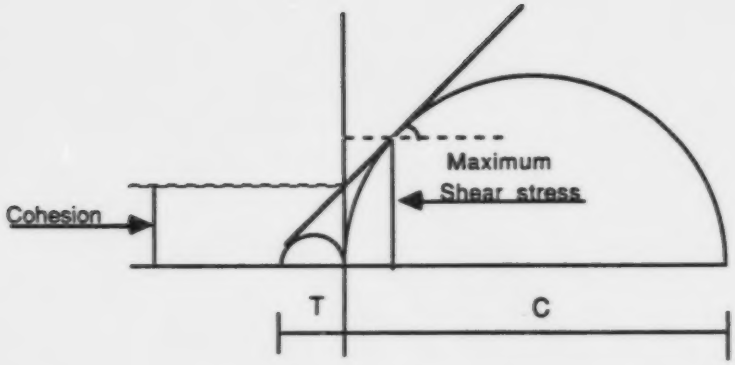

Figure 1 Mohr diagram

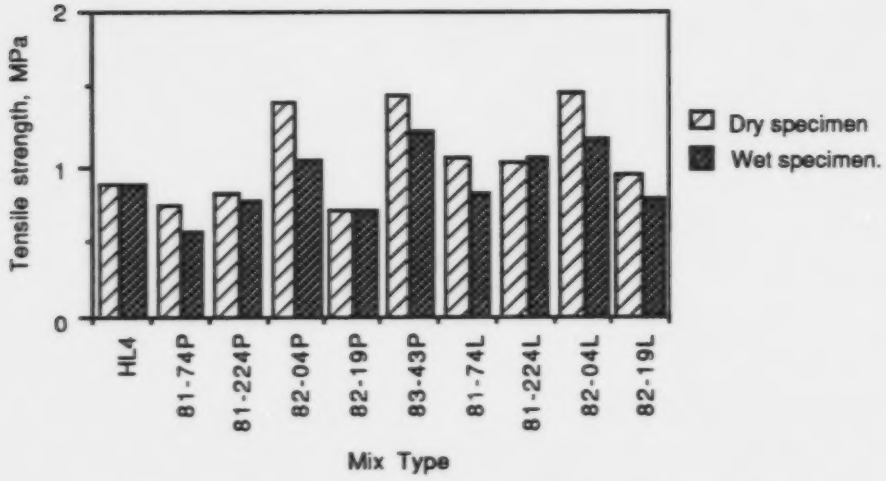

Figure 2 Tensile strength comparison of dry and wet mixes

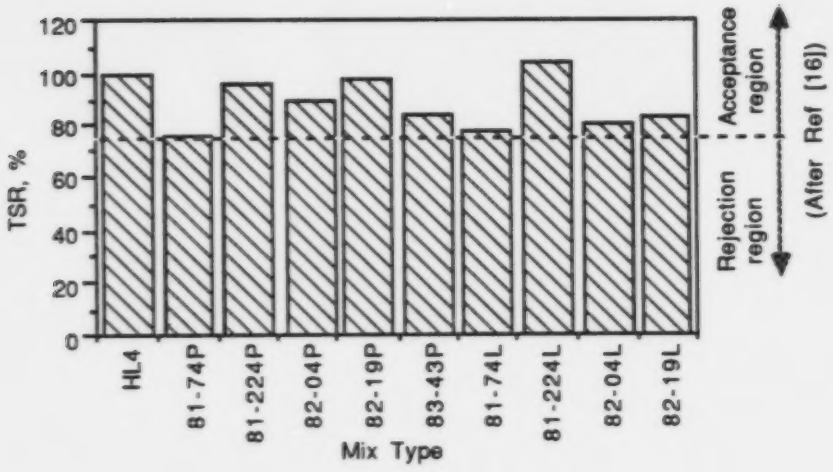

Figure 3 TSR comparison of various mixes

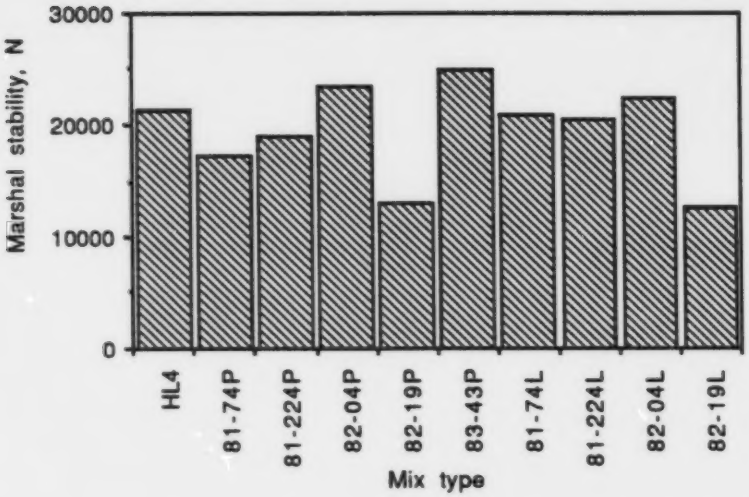

Figure 4 Marshall stability comparison of various mixes

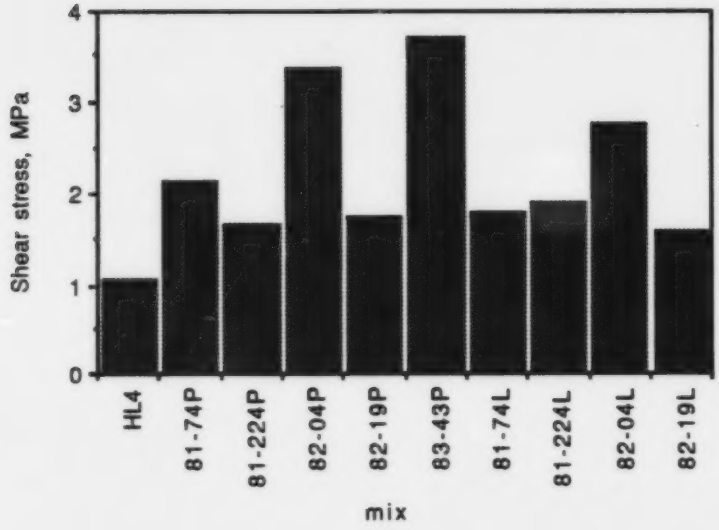

Figure 5 Shear stress comparison of various mixes

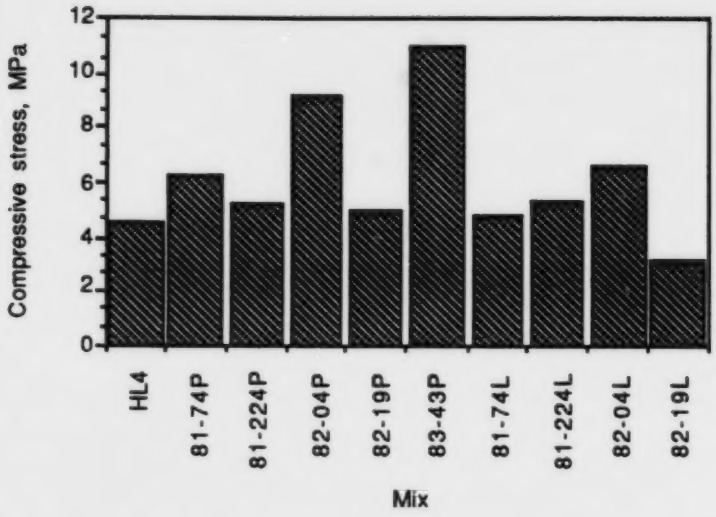

Figure 6 Compressive stress comparison of various mixes

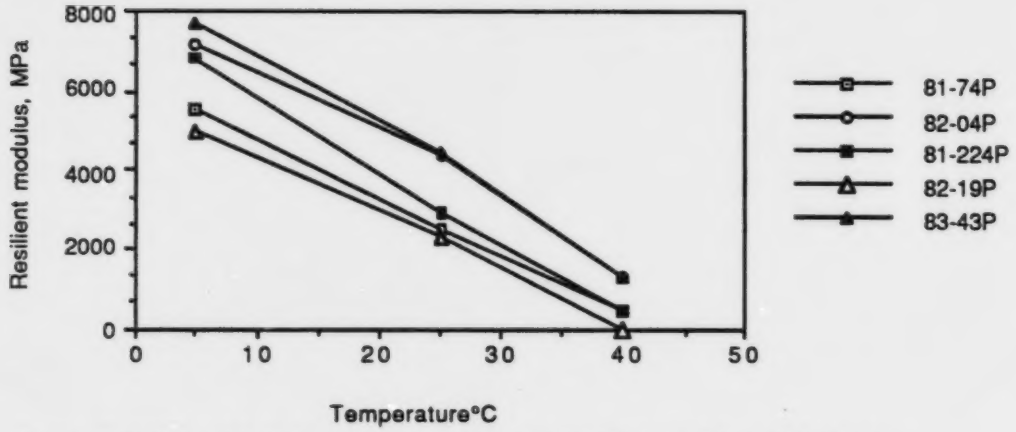

Figure 7 Relationship between temperature and resilient modulus of plant mixes

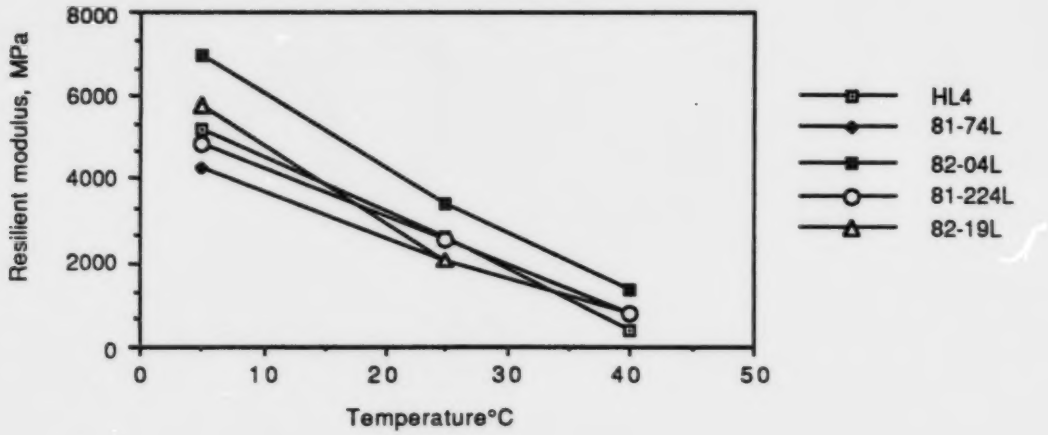

Figure 8 Relationship between temperature and resilient modulus of laboratory mixes

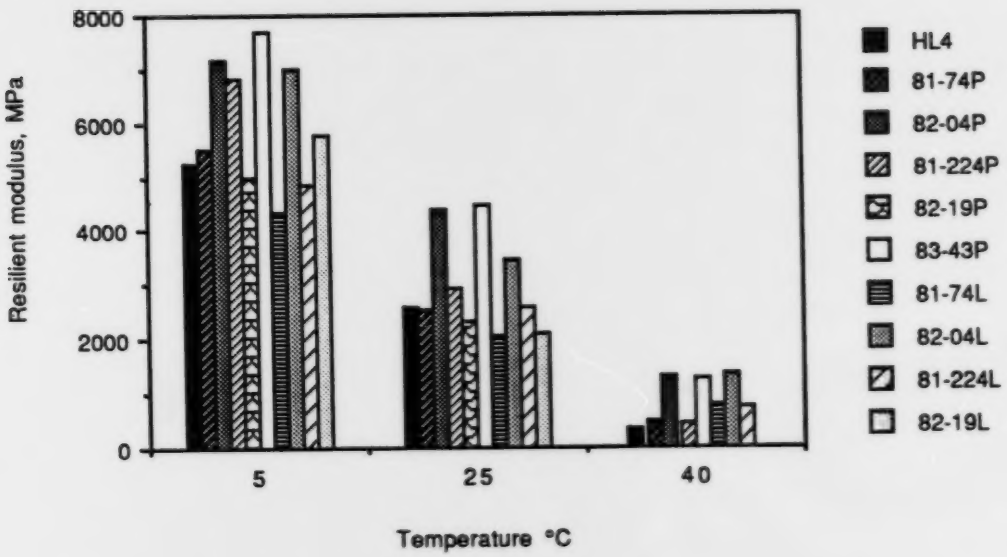

Figure 9 Comparison of resilient moduli of various mixes at different temperatures

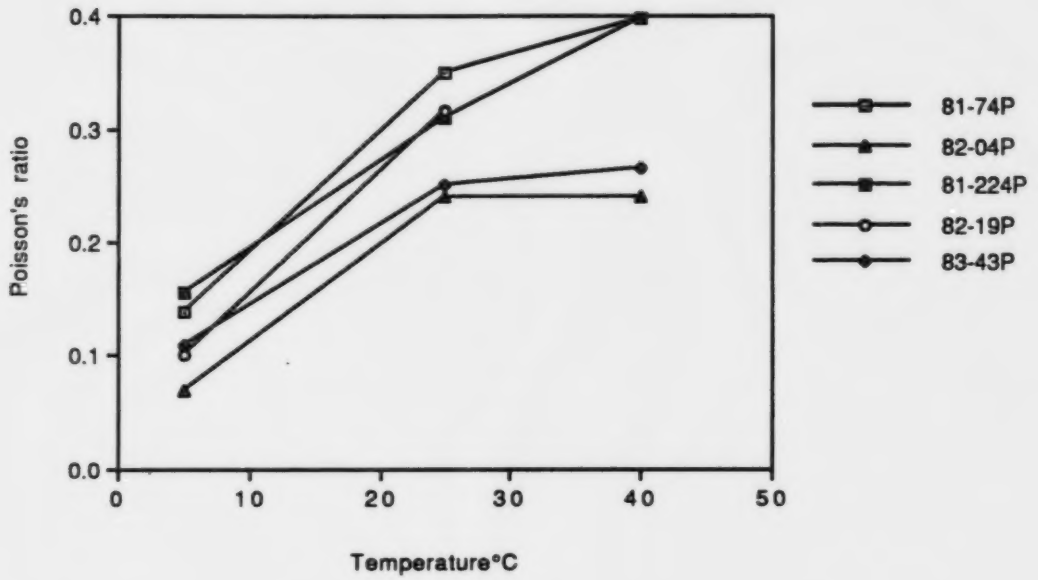

Figure 10 Relationship between Temperature and Poisson's ratio of plant mixes

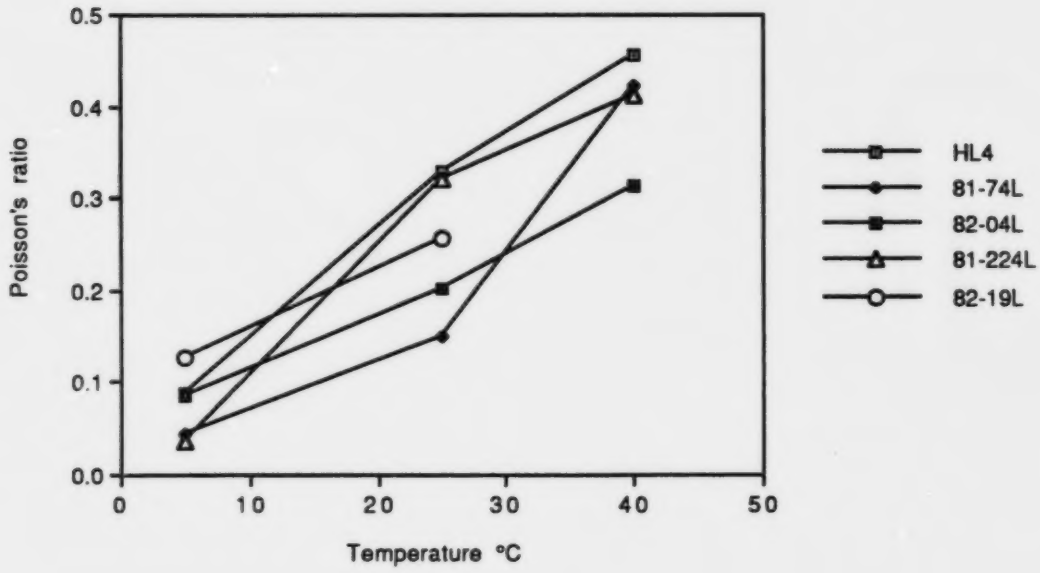

Figure 11 Relationship between temperature and Poisson's ratio of laboratory mixes

Table 1: Mix Design Properties of Recycled Hot Mixes and HL4 Mix

CONTRACT NUMBER	RECYCLING RATIO	ASPHALT CEMENT, %			Stability N	Flow	VMA %	Ret., % 4.75mm	Air Voids %
		ADDED	TOTAL	PEN					
81-224	60/40	2.7	5.2	300/400	10,000 (16,887)	9.2 (11.4)	N/A (14.6)	40	2.8 (1.4)
82-19	30/70	4.5	5.3	150/200	10,000 (12,080)	13.5 (14.2)	12.5 (14.3)	45	1.6 (1.0)
82-60	60/40	3.2	5.6	B.P.500	10,000 (10,346)	8.8 (8.8)	15.0 (15.0)	40	3.0 (3.3)
81-74	50/50	2.3*	5.0	300/400	16,760 (14,469)	12.5 (12.1)	N/A (14.8)	45	2.8 (2.8)
82-04	70/30	1.7	5.3	150/200	16,280 (17,658)	13.8 (13.5)	15.6 (15.3)	36	3.0 (1.9)
83-07	50/50	2.6	5.1	B.P.500	7,800 (10,884)	9.0 (11.4)	14.0 (13.9)	39	3.0 (1.5)
83-43	25/75 (DFC)	3.8	5.3	85/100	23,000 (24,042)	18.1 (17.4)	11.8 (9.5)	45	2.7 (2.6)
HL4	-	-	5.3	85/100	13600	10.4	13.8	45	4.0

* 0.5% antistripping agent added

Plant check results are given in parentheses

Table 2: AADT for Different RHM Test Sections

CONTRACT	REGION	HWY	LOCATION	YEAR					
				81	82	83	84	85	86
81-224	NORTH WESTERN	11	30km East of HWY633	600	550	550	500	500	500
82-19	CENTRAL	649	10km N. of Bobcaygeon	1000	1000	1000	950	950	950
82-60	EASTERN	62	2km N. of combermere			1250	1350	1350	1450
81-74	EASTERN	60	35km East of Renfrew	1500	1500	1500	1350	1350	1450
82-04	SOUTH WESTERN	21	5km S. of Thamesville	1900	2100	2100	2100	2100	2100
83-07	SOUTH WESTERN	2	6km W. of Thamesville			4600	4300	3600	3600
83-43	CENTRAL	QEW	Niag. Falls	26,200	26,000	28,200	30,000	32,150	33,400

Table 3 Recovered Asphalt Binder Properties of RHM

Contract	RAP		RHM	
	Pen @25°C mm	K. Visc. @ 135°C mm^2/sec	Pen @25°C mm	K. Visc. @ 135°C mm^2/sec
81-74	35	1073	53	457
81-224	31	517	57	326
82-04	28	508	36	498
82-19	20	1456	63	401
83-43	22	1167	30*	708*

* Recovered one year after construction

Table 4 Aggregate Description for Various Mixes

Mix Identification	Description	
	CA	FA
81-74	Crushed gravel containing Palaeo-zoic carbonates and marble granite	Silica rich natural sand
81-224	Crushed igneous gravel with mainly granite and granite gneiss	Silica rich natural sand
82-04	Crushed carbonate gravel with < 10% granite and gneiss	Silica rich natural sand
82-19	Crushed limestone gravel	Carbonate & silicate natural sand
83-43	Steel slag (DOFASCO)	Steel slag (DOFASCO)
HL-4	95% carbonate rock, 5% granite	95% carbonate rock, 5% granite

Table 5 Aggregate Gradations for HL4 and RHM Mixes

Mix		% Retained											
		Sieve size, mm								Sieve size, µm			
			16	13.2	9.5	6.7	4.75	2.36	1.18	600	300	150	75
HL4	CA			23.2	68.5	89.0	98.1	98.3	98.5	98.7	98.8	99.0	99.2
	FA						1.0	20.1	39.0	58.6	82.4	92.4	96.7
	Final			10.5	31.0	40.3	45.0	55.5	65.9	76.7	89.8	95.4	97.8
81-74	RAP			3.2	13.4	26.0	36.8	50.7	60.9	71.5	84.1	91.0	94.8
	CA		4.3	20.4	63.7	88.3	92.7	93.6	94.5	95.4	96.2	97.1	98.0
	FA						0.4	1.4	5.3	21.0	60.6	88.8	95.9
	Final		1.3	7.5	25.1	38.4	45.0	52.2	58.3	67.2	82.4	92.3	96.0
81-224	RAP		1.3	5.8	24.0	38.9	49.0	62.4	72.9	81.2	87.6	91.7	94.9
	CA		2.8	17.2	55.7	81.6	94.6	95.2	95.7	96.3	96.9	97.4	98.0
	FA					1.0	9.1	29.4	51.3	72.2	87.8	95.1	97.9
	BLSA	0.5	1.0	1.6	3.6	5.7	8.3	17.1	32.2	55.8	85.3	97.5	99.4
	Final		1.0	4.9	19.6	31.2	40.0	52.6	94.9	77.0	88.1	93.7	96.4
82-04	RAP	2.0	4.0	7.0	18.0	33.0	44.2	57.0	64.0	71.0	84.0	93.0	95.5
	CA		0.3	8.5	59.9	88.7	98.1	98.3	98.6	98.8	98.0	89.3	99.5
	FA				0.5	1.0	2.0	4.1	8.0	14.5	33.9	81.7	94.2
	Final	1.4	2.8	5.3	15.6	27.5	36.0	45.4	51.2	57.8	71.8	90.4	95.4
82-19	RAP	1.3	6.7	10.0	23.0	34.7	45.0	59.7	70.3	79.0	87.0	93.0	96.0
	CA		3.5	19.5	63.4	88.5	97.6	97.9	98.2	98.5	98.8	99.1	99.0
	FA						1.9	16.4	35.1	51.5	70.2	83.1	91.1
	BLSA				1.4	2.9	5.3	12.3	24.1	39.8	65.6	88.5	96.1
	Final	0.4	3.1	9.0	26.8	38.3	45.0	53.7	62.9	71.9	83.1	92.1	96.2
83-43	RAP			1.0	8.0	22.0	32.0	46.0	58.0	68.0	80.0	89.0	92.8
	CA			2.0	34.6	69.7	94.5	95.2	95.9	96.7	97.4	98.1	98.8
	FA							39.1	62.4	75.4	85.0	91.1	95.2
	Final			1.0	15.6	32.8	45.0	62.9	74.6	92.2	88.7	93.4	96.0

Table 6 Experimental design for moisture induced damage tests

Mix		Test condition		Total
		Dry	Saturated	
81-74	Plant	2	2	4
	Lab	2	2	4
81-224	Plant	2	2	4
	Lab	2	2	4
82-04	Plant	2	2	4
	Lab	2	2	4
82-19	Plant	2	2	4
	Lab	2	2	4
83-43	Plant	2	2	4
	Lab	-	-	-
HL4	Lab	2	2	4

Note: Two samples per cell

Table 7 Experimental design for Tension, Compression, and Stability Tests

Mix		Tension test at 21 °C	Compression Test at 21 °C	Marshall stability test at 60 °C
81-74	Plant	2	2	2
	Lab	2	2	2
81-224	Plant	2	2	2
	Lab	2	2	2
82-04	Plant	2	2	2
	Lab	2	2	2
82-19	Plant	2	2	2
	Lab	2	2	2
83-43	Plant	2	2	2
	Lab	-	-	-
HL4	Lab	2	2	2

Note: Two samples per cell

Table 8 Experimental Design for Resilient Modulus Tests

122		Temperature °C		
		5	25	40
81-74	Plant	2	2	2
	Lab	2	2	2
81-224	Plant	2	2	2
	Lab	2	2	2
82-04	Plant	2	2	2
	Lab	2	2	2
82-19	Plant	2	2	2
	Lab	2	2	2
83-43	Plant	2	2	2
	Lab	-	-	-
HL4	Lab	2	2	2

Note:- Two samples per cell

Table 9 Moisture Induced Damage Test Results

Description		Specimen Type										
		81-74		81-224		82-04		82-19		83-43		HL4
		plant	lab	plant	lab	plant	lab	plant	lab	plant	lab	lab
Average degree of saturtation after partial saturation (%)		66.9	71.0	71.8	68.3	72.8	64.3	65.0	70.0	61.6	-	65.4
Average degree of saturtation after moisture condtioning (%)		88.7	97.4	83.0	74.9	95.1	88.9	79.6	78.5	77.3	-	78.8
Average swell after partial saturation (%)		-0.44	-0.38	-0.54	-0.17	-0.24	0.25	-0.44	-0.04	-0.71	-	-0.38
Average swell after moisture condtioning (%)		0.85	1.25	0.31	0.17	0.91	1.02	0.14	0.34	-1.61	-	0.08
Average tensile strength, MPa	Dry	0.75	1.05	0.81	1.01	1.41	1.46	0.72	0.94	1.45	-	0.88
	Saturated	0.57	0.82	0.77	1.05	1.02	1.17	0.70	0.78	1.22	-	0.88
Tensile strength ratio(%)		76	78.1	95.1	104	89.5	80.1	97	82.9	84.1	-	100

Table 10 Marshall Test Values for Various Asphalt Mixes

Mix	Stability (N)	Voids, %	Flow	BRD	MRD	Marshall stiffness, MPa [17]
HL4	21,350	5.0	9.4	2.428	2.557	140
81-74P	17,174	2.4	13.3	2.438	2.499	80
81-74L	20,794	3.5	11.6	2.416	2.506	111.14
81-224P	19,001	3.3	12.3	2.404	2.484	95.77
81-224L	20,384	2.1	15.4	2.453	2.507	82.06
82-04P	23,378	4.0	13.9	2.394	2.494	104.27
82-04L	22,378	5.0	12.8	2.366	2.491	108.39
82-19P	13,067	0.6	18.5	2.468	2.482	43.79
82-19L	12,547	0.9	15.5	2.469	2.490	50.188
83-43	24,922	3.8	20.1	2.831	2.942	76.87

Table 11 Comparison of Shear Deformation Parameters of Different Mixes

Mix Type	Tensile Stress, MPa	Comp. Stress, MPa	Shear Stress, MPa	Cohesion MPa	Φ Deg.
HL4	0.272	4.550	1.04	0.56	62.5
81-74P	0.972	6.332	2.15	1.24	47.2
81-74L	0.989	4.704	1.783	1.02	45.3
81-224P	0.679	5.147	1.650	0.935	50.1
81-224L	0.916	5.268	1.872	1.098	44.7
82-04P	1.752	9.135	3.355	2.0	42.7
82-04L	1.963	6.540	2.748	1.791	32.8
82-19P	0.834	4.944	1.739	1.02	45.3
82-19L	1.163	3.064	1.567	0.943	31.2
83-43P	1.683	10.89	3.705	2.14	47.1

Table 12 Static and Dynamic Load Values for Resilient Modulus Testing

Temperature °C	Expected Stiffness of Material (MPa)	Dynamic load amplitude (N)	Initial static Load (N)
40	Weak (< 300)	45-90	0-5
	Moderate (300-900)	90-140	5-10
	High > 900	140-280	5-10
25	Moderate < 5000	400-500	10-40
	High > 5000	500-1000	10-40
5	4000-9000	1000-1500	50-200

Table 13 Resilient Modulus and Poisson's Ratio Values for Various mixes

Mix type	Temperature °C		
	5	25	40
HL4	5250 (0.088)	2591 (0.33)	363 (0.455)
81-74P	5519 (0.139)	2531 (0.35)	469 (0.397)
81-74L	4326 (0.043)	2055 (0.15)	773 (0.421)
81-224P	6806 (0.155)	2933 (0.31)	428 (0.398)
81-224L	4847 (0.036)	2569 (0.32)	744 (0.412)
82-04P	7160 (0.069)	4388 (0.24)	1311 (0.239)
82-04L	6981 (0.085)	3432 (0.203)	1363 (0.314)
82-19P	4973 (0.101)	2317 (0.316)	-
82-19L	5760 (0.128)	2083 (0.257)	-
83-43P	7704 (0.110)	2055 (0.25)	773 (0.265)

Note: Figures shown in parentheses are Poisson's ratio values